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Overview of anti-islanding US patents for grid-connected inverters

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ABSTRACT

Recent rapid interest in renewable energy generation, especially high penetration of the grid-connected photovoltaic system, is imposing new challenges to the anti-islanding protection. In practice, there is a potential risk of failure for anti-islanding protection due to the interaction between different islanding detection algorithms. It is of great importance to identify which kind of islanding detection methods are used in field applications for further analysis of this interaction problem. Although many anti-islanding detection methods have been reported in the last decades, most of them have been presented and discussed from the academic point of view, and they are very interesting, but complicated to implement and might not be practical for real applications. Therefore, the objective of this paper is to provide a comprehensive review of relevant international patents to find out the potential anti-islanding algorithms in real applications, which would be useful for the further investigations of interaction between different anti-islanding algorithms in a real distributed grid.

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1. Introduction

Integration of renewable energy systems into grid is an effective solution to the electric energy shortage and environmental pollution, and gaining more and more attention all over the world. A number of technical challenges may arise with increased grid-connected renewable energy systems. One of the most important issues is how to achieve the fast and reliable anti-islanding protection [1–4].

Islanding refers to the condition in which a grid-connected inverter continues to power the local loads even though electrical grid power from the electric utility is no longer in service [5]. Some hazards associated with islanding include

(1) Utility workers sent out to repair the utility grid may not be aware that the portion of the utility grid is receiving power from a grid-connected renewable energy system even though the utility grid itself is not powered. Serious injury or death may occur if the utility worker makes contact with a portion of the utility grid.
(2) The utility has no control over the voltage or frequency supplied to an islanded location which creates the possibility of damage or potential hazards to the local devices and equipments.
(3) It may interfere with restoration of normal service and prevent automatic re-connection of devices. Therefore, the anti-islanding detection and protection is a mandatory function for the grid-connected renewable energy systems.

Many anti-islanding detection methods have been reported in the last decades. Most of them have been presented and discussed from the ***academic*** point of view. For example, wavelet-based islanding detection [6–8], fuzzy rule-based islanding detection [9], neural network based islanding detection [10], and so on. They are very interesting and insightful, but complicated to implement and might not be practical for commercial applications.

There is an interesting question which kind of anti-islanding method is used for grid-connected inverter in industrial fields? It is of great importance, since the interactions between different anti-islanding algorithms in practical applications become more and more significant with the high penetration of grid-connected renewable energy systems, and there is a high potential risk of failure about anti-islanding detection due to the their interactions. Therefore, it is crucial to carry out further investigations about the interaction analysis of the anti-islanding algorithms in practical applications to avoid anti-islanding failure. Unfortunately, the detailed information about anti-islanding algorithms from the relevant inverter manufacture companies is unavailable for commercially confidential reasons.

On the other hand, there is a way of investigating the international patents to find out the potential anti-islanding algorithms for practical applications. The objective of the paper is to review the US patents of the international electrical corporations to provide a new insight of the anti-islanding issue. Note that only patents from international electrical corporations are discussed in this paper, aiming at providing a useful guidance for commercial applications.

2. Anti-islanding patents

Fig. 1 illustrates the block diagram of grid-connected inverter. The islanding occurs when the utility grid is disconnected. In general, islanding detection methods of grid-connected inverters can be classified into two categories. One is the passive method, and the other is the active method.

Passive methods are based on local monitoring of the electrical signals at the inverter output terminal, such as, under or over voltage, under or over frequency, rate of change of frequency, phase jump, and harmonics. In an early patent [11], the islanding detection is achieved by the voltage relay, frequency relay and distortion relay. In another patent [12], the RMS voltage changes are utilized as an indicator of islanding. However, when the power supplied by the inverter and the power of the local load are balanced, the electrical components at the inverter output remain unchanged, and the passive methods fail to detect the islanding. It is the so-called non-detection zone (NDZ). That is why most of the islanding detection patents are active. Following will present and classify the active islanding detection patents.

2.1. Phase disturbance method

2.1.1. Phase shift with positive feedback [13]

In the patent of Ballard Power Systems Corporation, it introduces a small intentional phase disturbance for the output voltage of the inverter in each voltage cycle. This small phase angle shift can be a positive, negative or random value. The accumulated small phase angle error is corrected at each voltage cycle in synchronization with the grid. If the grid is lost, the small phase angle shift will not be corrected, causing an initial frequency change. The initial frequency change can be accumulated, and frequency drift will occur, from cycle to cycle. When the frequency drift rate is over a preset level, for example 2 Hz/s, a positive feedback loop is enabled for accelerating the frequency drift. When the frequency drift is over a preset level, the islanding can be confirmed.

Because the injection phase angle is very small and corrected in each voltage cycle, it does not cause the frequency shift, power factor change and extra harmonics if the grid is present. On the other hand, it can detect the islanding operation of an inverter without NDZ in case of grid disconnection. Also, it can be extended to multi-inverter applications on condition that a synchronization mechanism is enabled to avoid canceling each other's effects.

2.1.2. Phase shift with PLL [14–16]

In the patent of Enphase Energy Inc., it injects a small phase shift through the Digital Phase Locked Loop (DPLL). A phase shift of magnitude 50 μs over a period of one cycle is injected at 0.5 s

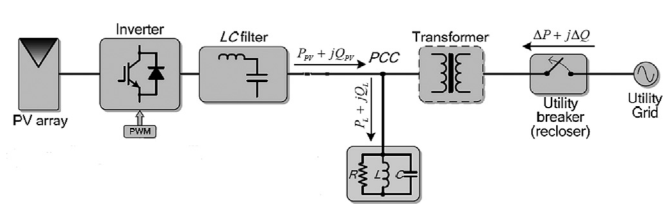

Fig. 1. Block diagram of grid-connected inverter.

intervals. Such an injected phase shift represents a phase shift of one degree and causes an insignificant distortion to the current injected into the grid. The alternative method may utilize different phase shift magnitudes, durations, and/or injection intervals.

While the grid-connected inverter remains connected to the utility grid, the DPLL produces a certain phase error response as a result of the injected phase shift. If the inverter becomes disconnected from the grid, the DPLL produces a different phase error response as a result of the injected phase shift. The islanding can be detected by the phase error response of the DPLL.

2.1.3. *Intermittent bidirectional phase shift [17,18]*

In the patent of PV Powered Inc., an intentional phase shift of current injection from the inverter into the grid periodically. The method alters the direction of phase shift in pairs. For instance, if a first phase shift is forward, the second phase shift (e.g. 10 cycles later) will be forward, the third phase shift will be backward, the fourth phase shift will be backward, the fifth phase shift will be forward, and the pattern will repeat.

Under normal operation, the PCC voltage is not be affected by the intentional phase shift of current injection due to the stiff grid. In an islanding situation, the PCC voltage will follow the phase shift of the inverter output current. The anti-islanding protection is enabled if the frequency change caused by the intentional phase shift is beyond the threshold value.

It should be noted that there is a tradeoff between speed of detecting an islanded condition and overall power quality. If a phase shift in the inverter current occurs every cycle, then an islanded condition can be detected quickly, but the inverter will have poor power quality due to the abruptly shifted current in this patent.

Conversely, if the current is phase shifted only once a second (every 60 cycles for a 60 Hz grid), there are only one or two chances to detect the islanding within the two-second period required. A period of approximately 10 cycles between phase shifts might be a good compromise. For a 60 Hz grid, a 10-cycle interval will give 12 chances for an inverter to detect the islanding condition.

2.1.4. *Phase shift with correlation function [19]*

As discussed above, the conventional phase shifts can be large and have an adverse impact on the inverter's output current and voltage at the point of common coupling (PCC). In order to detect an islanding condition without adversely affecting the inverter's power quality, the patent of Xantrex Technology Inc. introduces a small perturbation to the phase in the output current of the inverter. In grid-connected mode, this phase shift pattern has no impact on the frequency of the PCC voltage. However, in islanding mode, this phase shift will cause the PCC voltage frequency to deviate from nominal. Changes in the output current phase thus correlate well with the voltage frequency. A covariance index is used to correlate the phase shift with the voltage frequency. In an islanding configuration, this covariance index will rise sharply as the phase shifts almost immediately begin to cause voltage frequency deviation. When the covariance index exceeds a predefined threshold, a second phase shift with large size is introduced in the output current. Therefore, the PCC voltage frequency will change quickly to fall outside the nominal, and the islanding can be detected.

Fig. 2 depicts a flowchart of the anti-islanding algorithm. In a first loop, the algorithm introduces no phase shift in the output current of the inverter for 60 AC cycles. A small, continuous, positive phase-shift is introduced in the output current for 4 AC cycles. The algorithm introduces no phase shift for 1 AC cycles and the output voltage frequency is measured. A small, continuous, negative phase-shift is introduced in the output current for 4 AC cycles, and the voltage frequency is measured. The algorithm calculates a covariance index based on the phase shift in the output current and the output voltage frequency of the inverter. The algorithm determines whether the calculated covariance index exceeds a predefined threshold, and, if not, the algorithm loops back to begin another loop of introducing small perturbations into the output current.

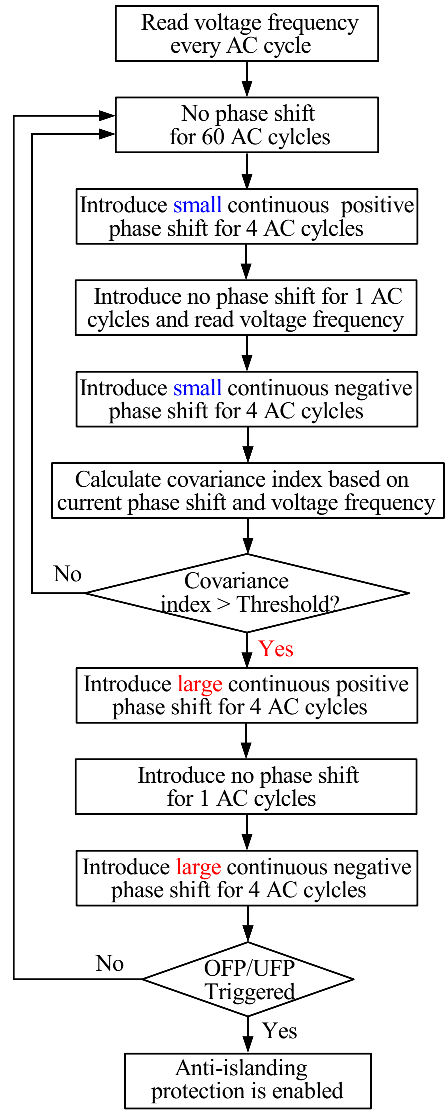

Fig. 2. Flowchart diagram of anti-islanding protection based on the phase shift with correlation function.

On the other hand, if the covariance index exceeds the predefined threshold, the algorithm enters a second loop by introducing a large, continuous, positive phase shift for 4 AC cycles in the output current. No phase shift is introduced for 1 AC cycle, and the algorithm introduces a large, continuous, negative phase shift for 4 AC cycles in the output current. The output voltage frequency is measured, and if it falls outside the OFP/UFP protection window, the anti-islanding protection is enabled. However, if the output voltage frequency is still inside the OFP/UFP protection window, the anti-islanding algorithm loops back to restart small perturbations into the output current. The logic here is to prevent a nuisance trip caused by a possible grid transient.

The major advantage of this anti-islanding algorithm is that it can guarantee the reliable trip against islanding while maintain the minimum perturbation in inverter's normal operation.

2.2. Frequency-disturbance method

2.2.1. Frequency drift with positive feedback [20]

In the patent of Georgia Tech Research Corporation, it is well known as the active frequency drift with positive feedback (AFDPF). It measures the frequency deviation between the grid and the inverter, and then applies the measured frequency deviation to the inverter output current with a positive feedback loop. When islanded, the frequency will drift outside the nominal. Therefore, the islanding can be detected.

2.2.2. Frequency drift with acceleration function [21]

In the patent of Plug Power Inc., it utilizes the frequency drift with acceleration function for the islanding detection. The acceleration function can be linear, geometric, exponential, or another increasing function so that disturbances on the grid are minimal except during islanding conditions, whereupon the system becomes unstable and quickly trips off. Similar to AFDPF, it minimizes the impact of the scheme under normal conditions, but creates a positive feedback that accelerates the response in islanding situation. Its unique feature lies in that the acceleration function is versatile to select for the islanding detection.

2.2.3. Bidirectional frequency disturbance [22]

In the patent of Sharp Kabushiki Kaisha, the inverter alternately increases and decreases the inverter output frequency relative to the rated frequency. Even when the frequency varying effect due to the load cancels each other in a certain period, they stop canceling each other in the next period. Also a positive feedback loop having the relatively steep slope can eliminate this relation of cancellation, so that the output frequency varies greatly. Therefore, the islanding operation state can be detected regardless of the power balance with respect to the load.

2.2.4. Random frequency disturbance [23,24]

In the patent of Ballard Power Systems Corporation, it utilizes the random noise to perturb the frequency to eliminate a need for correcting the phase angle or the frequency of the inverter at every cycle to match the grid frequency, which greatly improves the harmonic content and direct current offset of the inverter current. The random noise is generated by a noise generator at every interval and is injected as a tri-state number sequence which can assume a positive value, a zero value, or a negative value. The random noise generator generates a band limited white noise. The random sequence generation can be expressed as follows. Noise=rand( )MOD3−1, where rand( ) function generates a random number which lies between 0 and 32,767. It is then divided by 3 to get the remainder, which will be either 0 or 1 or 2. Deducting 1 from the remainder yields −1 or 0 or +1.

On loss of the grid, a frequency drift of the output voltage is detected and a positive feedback is activated that accelerates the drift. Therefore, the islanding can be easily identified. The major advantages are as follows. It utilizes a white noise to perturb the frequency and thus does not introduce any resonance mode to the system which could interact with the load. It utilizes random noise injection works well even for an unbalanced grid voltage system.

2.2.5. Frequency disturbance with a maximum function [25,26]

In the patent of PV Powered Inc., it utilizes a frequency disturbance with a maximum function to determine islanding. A flow diagram is illustrated in Fig. 3 for detecting islanding.

First, the system measures the PCC voltage and extracts the instantaneous frequency from the measured PCC voltage. Second, the system determines if the extracted grid frequency is greater than a threshold frequency associated with a likely islanding condition. If the extracted grid frequency is above the threshold frequency, the anti-islanding protection is enabled. If the extracted frequency does not exceed a threshold frequency, then the system injects a frequency bias into the output current. The injected frequency bias is determined by a maximum function. More specifically, $\Delta F = \max(S\Delta F_o,\ G\Delta f)$, where ($S$) is a sign of the frequency error, (ΔF_o) is the disturbance drift value, (G) is a gain, and (Δf) is the frequency error, which is determined by the equation $\Delta f = f_m - f_{ave}$, where (f_m) is an instantaneous frequency of the grid and (f_{ave}) is an average frequency of the grid.

When the grid is connected with the inverter, the frequency bias of the grid is almost zero. However, during islanding conditions of power balance specified by IEEE Std.1547, there may be little or no measured frequency error. In this case, the "max" function in Fig. 3 enables the system to determine islanding by introducing a frequency disturbance. Therefore, the islanding can be detected even when the load is well matched to the inverter power.

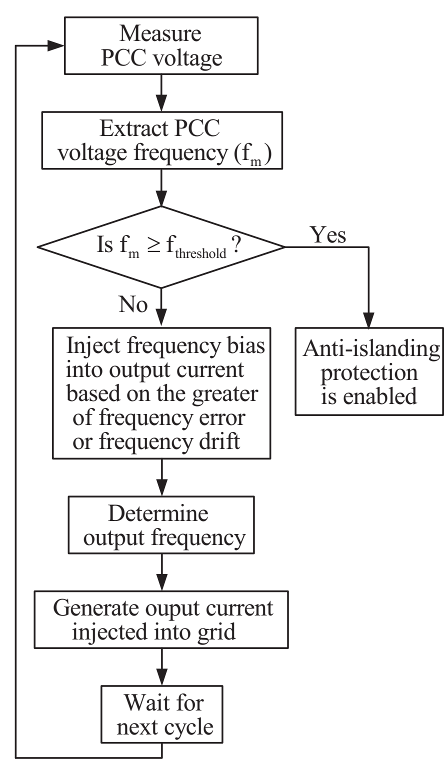

Fig. 3. Flowchart diagram of the islanding detection method based on frequency disturbance.

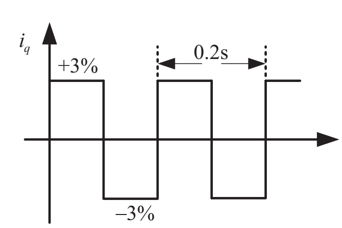

Fig. 4. Diagram of reactive current disturbance for islanding detection.

2.2.6. Sinusoidal frequency disturbance [27]

In the patent of Caterpillar Inc., a sinusoidal frequency disturbance is used for islanding detection. When grid is connected, the output power delivered by inverter may oscillate around the desired power of grid and critical load. The amplitude of the frequency disturbance is small to keep the power oscillation at an acceptable level. However, when an islanding condition occurs and the loads and inverter are matched, the output power of inverter cannot oscillate since the loads can only extract fixed amount of power from the inverter. Therefore, the islanding condition can be detected if the amplitude of oscillation is below a threshold. The major difference from the other frequency disturbance methods is that the islanding is determined by the power oscillation amplitude, instead of the frequency drift.

2.3. Power disturbance method

2.3.1. Active power disturbance [28–29]

The early patent from Canon Kabushiki Kaisha in1997 introduces a power disturbance for anti-islanding protection [28]. It includes a switch for connecting or disconnecting a power changing device for changing the power to the grid. A pulse circuit generates a periodic pulse signal for the switch. The major disadvantage of this early patent is that an additional device is required for the power disturbance. Also, it needs synchronizing the power disturbance in case of for multiple grid-connected inverters. Otherwise, it may fail because the asynchronous power disturbances from different inverters may cancel each other.

In the patent of Magnetek S.p.A [29], a power disturbance is used for anti-islanding protection. The disturbance imposed on the inverter output power is a reduction of the power. After a time interval, The PCC voltage remains unchanged, which indicates that the inverter is not isolated from the grid, and therefore it is not an islanding. After that, the power delivered by the inverter is restored to the normal value. On the other hand, the islanding can be confirmed if the PCC voltage changes with the inverter power reduction.

2.3.2. Reactive power disturbance [30–32]

In the patent of Square D Company [30], the anti-islanding algorithm introduces the amount of reactive power disturbance of the inverter and determines whether this change shifts the inverter's output frequency. If the frequency change caused by the reactive power disturbance is beyond the predefined threshold, the islanding is confirmed. Another patent from Eaton Corporation [31] employs the controlled reactive power injection by the number of inverters, and detects islanding responsive to a number of changes of PCC voltage.

In the patent of ABB Schweiz AG [32], it introduces a reactive power disturbance with square-wave reactive current for islanding detection. The disturbance is shown in Fig. 4, where the reactive current is generated at a frequency of 5 Hz with a magnitude of ± 3 percent of the rated current. The frequency of this square-wave reactive current is 5 Hz. And it can also be set to another value above or below 5 Hz, as long as there are a sufficient number of disturbance for islanding detection during the 2 s period.

2.4. PCC voltage disturbance method

2.4.1. Direct voltage feedback [33]

In the patent of Solarbridge Technologies Inc., it senses PCC voltage waveform, and then directly controls the inverter output current to track a reference current waveform with the PCC voltage waveform, and enables the anti-islanding protection when the PCC voltage is sensed to be outside a predetermined range. The inverter output current can be represented by the following equation. $I(s) = G(s)V_{pcc}(s)$, where $G(s)$ represents the desired functional relationship between PCC voltage and inverter output current. The flowchart of this method is shown in Fig. 5.

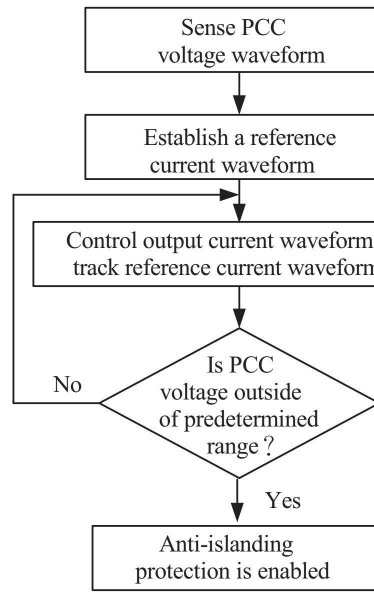

Fig. 5. Flowchart diagram of the islanding detection method based on direct voltage feedback.

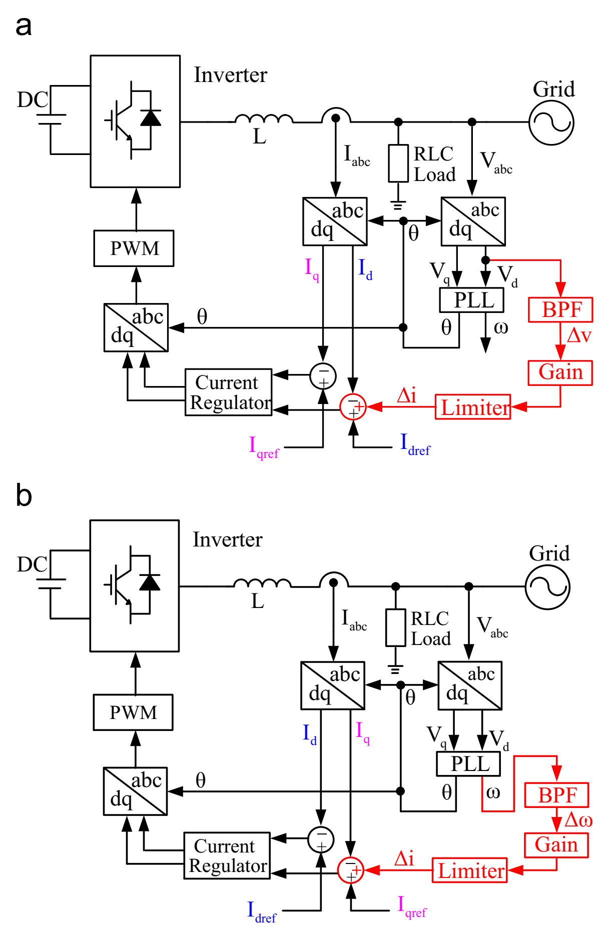

Fig. 6. Schematic diagram of the islanding detection method based on indirect voltage feedback. (a) Indirect voltage feedback to I_{dref}. (b) Indirect voltage feedback to I_{qref}.

2.4.2. Indirect voltage feedback [34]

In the patent of General Electric Company, it provides a family of PCC voltage based anti-islanding schemes for grid-connected inverters. The variation of the PCC voltage in one of the DQ coordinates, such as V_d or V_q, or the phase-locked loop output, such as frequency W, is fed back to the inverter current references in one of the DQ coordinates, such as I_{dref} or I_{qref}. As a result, when the inverters are islanded, the feedback loop of controller will drive both the voltage and frequency of the inverter away from their nominal ranges, which is an indicator of islanding.

Take Fig. 6 for example, the PCC voltage and inverter current signals are transformed from stationary coordinates (ABC) to rotating coordinates (DQ). A positive feedback loop is used for islanding detection.

More specifically, a voltage variation in one axis, such as V_d, resulting from a disconnected electrical grid, results in the voltage-variation Δv at the output of bandpass filter. Passing the voltage variation Δv signal through amplifier and limiter results in a current variation signal Δi at the output of limiter. The current variation signal Δi is added to the D-axis current reference signal I_{dref} and minus the D-axis current signal I_d, and then the integrated signal is passed to current regulator. The output of current regulator is transformed from DQ coordinates to ABC coordinates. After islanding, it will drive the PCC voltage magnitude and/or the frequency out of the nominal ranges with this positive feedback loop. Therefore, the islanding can be confirmed if the PCC voltage magnitude or frequency is beyond the threshold level.

In summary, the core of this positive feedback loop consists of a bandpass filter, an amplifier and a limiter, and the input and output of the positive feedback loop can be arranged so that Idref is modified by Vd, as shown in Fig. 6a.

Further considerations that should be noted is the parameter design of the positive feedback loop. If the band of the bandpass filter is too high, the feedback loop may be too noise sensitive, and if it is too low, the response of the anti-islanding controller may be too slow to meet the tripping requirement. Here, the band of bandpass filter was selected as being about 1 Hz to about 10 Hz, the gain of amplifier was selected to provide a positive feedback loop gain of about 20 dB, and the threshold level of limiter was selected to prevent the positive feedback from exceeding a pre-defined level during transient conditions.

In addition, other feedback loop arrangements can also be used so that I_{qref} is modified by frequency signal ω, as shown in Fig. 6b. These positive feedback loops cause the PCC voltage and frequency to be driven away from their nominal values, which is an indicator of islanding.

2.5. Harmonic disturbance method

2.5.1. High frequency disturbance [35–37]

In the patent of Visteon Global Technologies Inc. [35], the harmonic injections with different phase angles on each phase are utilized for islanding detection. The harmonic signal is injected into the grid so that the resulting impedance response can be measured. If the magnitude or phase angle of the measured impedance on any phase exceeds a predetermined threshold or deviates from a desired range, an islanding condition can be identified. In the patent of Samsung Electro-Mechanics Co. Ltd. [36], it utilizes a 9-order harmonic as the injection signal. The islanding can be confirmed if the 9-order harmonic component at PCC voltage is beyond the predetermined level. It allows the detection of islanding conditions even when the load is well matched to the generated power.

Another interesting patent is reported in [37] by Youtility Inc., it periodically injects a current spike at the zero-crossing of PCC voltage for islanding detection. The current spike causes a distortion in the form of a voltage deflection when an island exists.

By periodically injecting the current spike at zero-crossings, other inverters are, at this instant of zero crossing, not supplying any real power to the island. This is because those other inverters are also at their respective zero-crossing points based on grid synchronization.

Therefore, the result of the current spike to the island can be readily manifested and reliably detectable undisturbed by other inverters.

In addition, it is effective in case of multiple inverters due to the synchronized injection at the zero crossing. It is in contrast to conventional anti-islanding schemes, which are difficult to synchronize, and thus tend to fail to detect the islanding due to interfering with or canceling the effect of each other.

2.5.2. Low frequency disturbance [38]

In the patent of SMA Solar Technology AG [38], a low frequency harmonic is injected into grid for islanding detection. The frequency of the injected harmonic is very small (e.g. 0.5–5 Hz), and the harmonic amplitude is small, but still just large enough for changes in reactive power, which oscillates with the injected harmonic frequency.

The reactive power flow is measured on the grid side. If the grid is stable, this reactive power flow changes with the injected harmonic frequency. While islanded, the reactive power flow will depend on the load, and thus no longer varies significantly. Therefore, the islanding can be identified by monitoring the reactive power flow changes.

3. Discussion and conclusion

A comprehensive review on the islanding detection US patents for grid-connected inverters has been presented in this paper. Five kinds of islanding detection methods have been discussed. For most of these methods, there is a tradeoff between islanding detection time and power quality. Many readers might have a question which is the best islanding detection method. In fact, it is difficult to answer this question since each method has its advantages and disadvantages. But a more important question than that is how it could be when these islanding detection methods interact with each other. It is crucial because of the high penetration of grid-connected photovoltaic systems into the distributed grid, where these islanding detection methods might fail due to their interaction and cancellation. Therefore, our future researches would be carried out towards the interaction analysis of these islanding detection methods for the reliable anti-islanding protection. It should be noted that we mainly focus on the anti-islanding patent for small-scale grid-connected inverters in distributed grid. Other islanding patent for large-scale central PV plants or other kind of generators are beyond the scope of this paper. Please read [39–46] for a reference. Finally, it is expected that this review will serve as a useful reference guide to the researchers working in the area of anti-islanding protection for grid-connected inverters in a real distributed grid.

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